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THE ANAEROBIC FILTER FOR THE DENITRIFICATION OF AGRICULTURAL SUBSURFACE DRAINAGE

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Federal Water Pollution Control Administration
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A paper presented on May 7, 1969 at the Twenty-Fourth Annual Purdue Industrial Waste Conference, Lafayette, Indiana, by Thomas A. Tamblyn and Bryan R. Sword, Sanitary Engineers, Federal Water Pollution Control Administration, U. S. Department of the Interior, P. O. Box 2385, Fresno, California.

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Thomas A. Tamblyn and Bryan R. Sword*

California's San Joaquin Valley is one of the Nation's most fertile areas. Its full agricultural potential has, however, not been achieved, because of the lack of water. Vast water resource development projects have been constructed and still more are being planned to eliminate this critical water shortage.

As more water becomes available a corollary problem will become more significant: what to do with the increased quantity of saline wastewater that will be generated. Of the over 7 million acres (2.8 million ha) of irrigable land in the San Joaquin Valley, approximately 1.7 million acres (0.7 million ha) have been classified as potential drainage problem areas (Figure 1)--lands where brackish high water tables have or will become a problem (1).

The vast majority of the saline agricultural wastewater that is presently being generated within the Valley is discharged to the San Joaquin River. As the quantity of this waste increases, the waste load on the river would reach a point of extreme unacceptability. The San Joaquin River would become saline and downstream users would be deprived of a usable water supply.

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For these reasons, a system is now under construction to collect much of the saline drainage and transport it to a "safe" disposal site. The system will service 300,000 acres (120,000 ha) of the drainage problem area. It is being built by the U. S. Bureau of Reclamation to handle primarily the wastewater from the Federal San Luis Service Area. The State of California is also aware of the drainage problem and is making plans to service those areas outside of the area served by the Federal facility (San Luis Drain). The predicted quality of the waste to be carried by the San Luis Drain is presented in Table 1 (2).

Several extensive studies have been conducted to determine the possible effects of the discharge of this waste. Of all the chemical constituents present in the waste, the one most likely to create problems is nitrogen (3, 4).

This paper discusses one of the many investigations concerned with the "safe" disposal of the up to 580,000 acre feet ($7.2 \times 10^{}$ cu m) per year of saline water (subsurface drainage) that will be generated by the year 2020 (1). (This is only about 4 percent of the water to be applied to the Valley in the same period.) The investigation is part of a program being undertaken at the Interagency Agricultural Waste Water Treatment Center (IAWWTC) near Firebaugh, California and began in September 1967. The Center is operated jointly by the California Department of Water Resources (DWR), United States Bureau of Reclamation (USBR), and the Federal

Water Pollution Control Administration (FWPCA). The primary objective of the work at the Center is to determine if the nitrate-nitrogen content of subsurface drainage can be removed at a cost low enough to justify treatment and disposal to the San Francisco Bay System as opposed to ocean disposal.

Two basic techniques of nitrate removal are being studied: algae stripping and bacterial denitrification. The latter is being investigated in two types of vessels (or unit processes): deep ponds and anaerobic filters. Only the anaerobic filter studies are discussed herein.

Bacterial denitrification is one of several possible events in bacterial metabolism utilizing highly oxidized anions for the oxidation of organic matter (5). The overall process of bacterial denitrification can be expressed stoichiometrically, as a two-step or three-step reaction. Nitrate (NO_3^-) is reduced to nitrite (NO_2^-) and then from nitrite to molecular nitrogen (N_2) with or without the intermediate formation of hyponitrite (N_2O_2). The process can be shown to be thermodynamically sound (capable of producing energy for organisms utilizing it) (6). Several commonly occurring facultative bacteria are denitrifiers, for example, Escherichia coli. The occurrence of bacterial denitrification in existing sewage treatment plants is well documented and several pilot-scale units have been built and successfully operated for denitrification (7, 8, 9, 10).

In the anaerobic filter the waste is passed through a packed column-type reactor (a vessel containing an inactive medium).

The filter medium provides a solid support for the denitrifying bacteria. The advantage of the filter is that the solids retention time (SRT) of the unit is longer than its hydraulic detention time, without the need for effluent solids separation and recycle (11). Denitrification filters can be operated with upflow or downflow configurations, as long as the unit is kept anaerobic (or nearly so).

As previously mentioned, bacterial denitrification is part of a metabolic event in which organic matter is oxidized. Unless biodegradable organic material is present in adequate quantity, effective denitrification will not take place. Most agricultural tile drainage has a low organic content. Therefore, methanol is added to the waste prior to entry into the anaerobic filters operated at the Center. Methanol is not the only organic carbon source that could be used. It was initially selected on the basis of cost per volume of waste treated, efficiency of treatment, and ease of handling (12). In addition, of the organic supplements that have been investigated, methanol metabolism produced the lowest quantity of cell mass per unit of material metabolized (6).

EXPERIMENTAL PROCEDURES

In his initial feasibility study of the denitrification process for removal of nitrate-nitrogen from agricultural drainage waters, McCarty recommended that field studies be conducted to investigate design factors and to perfect high rate denitrification processes (12) [anaerobic filters]. To accomplish these objectives the study at the Center was designed to answer the following:

1. Is anaerobic filter denitrification feasible under field conditions?
2. Are medium size, texture, and sorptive quality significant?
3. What are the effects of long-term operation on treatment efficiencies?
4. What hydraulic detention time is required for efficient denitrification?
5. How does the quantity of organic carbon required for efficient denitrification under field conditions compare to the predicted quantity?

Apparatus

Three different sizes of anaerobic filters have been used: 4-, 18-, and 36-inch diameter. All of the filters were operated as upflow units. The 4-inch diameter filters, constructed of polyvinylchloride (PVC) pipe, had media bed depths of 6.5 feet. These filters demonstrated that the process was feasible under field conditions.

Once it was determined that the process worked, 18- and 36-inch diameter filters were constructed from concrete pipes sealed at one end. The influent distribution system for the 18-inch diameter units was a straight perforated PVC pipe extending across the filter bottom. A cross distribution system was placed at the bottom of the 36-inch diameter units with a 1/2 x 1/2-inch mesh media support screen placed approximately 4 inches above the flow

distributor. Media support screens were not used in the 18-inch diameter units. All filters were insulated to better model the temperature regime of large scale filters. To permit the extraction of samples from various points within the media beds, profile sampling systems were installed in all units. The flow to each unit is rotometer controlled with the organic carbon source injected into the influent just prior to entering the unit. Figure 2 is a schematic diagram of the upflow anaerobic filter denitrification process. Two of the 18-inch diameter units operated at the Center are shown in Figure 3.

Analytical Techniques

The routine chemical analyses used to monitor the operation of the filters were as follows:

1. Nitrogen Series--Nitrate, Nitrite, Organic Nitrogen, Ammonia Nitrogen, and Total Kjeldahl Nitrogen.
2. Orthophosphate
3. pH
4. Alkalinity
5. Dissolved Oxygen
6. COD
7. Suspended and Volatile Suspended Solids
8. Methanol

Analyses 1-6 were performed as directed in Standard Methods (13). In particular, nitrate-nitrogen was determined by the brucine method, and the orthophosphate analyses were performed using the stannous

chloride modification. Filtration of suspended and volatile suspended solids was accomplished with glass paper having a 0.45-micron pore size. Drying and incineration were carried out according to Standard Methods. Methanol was originally determined by a chromatropic acid method (14, 15, 16). After September 11, 1968, methanol determinations were made using a gas chromatograph with a carbowax column and a flame ionization detector.

Regular sampling intervals were established for the filters. Generally, routine sampling was completed by 9:30 A.M. each sample day, with selected samples being taken in the afternoon and occasionally every 3 hours for periods of 24 to 48 hours.

Influent and effluent nitrate, nitrite, and methanol concentrations were determined a minimum of three times per week. Influent and effluent total Kjeldahl organic, organic nitrogen, ammonia nitrogen, orthophosphate, pH, alkalinity, suspended solids, and volatile suspended solids were determined weekly. Influent dissolved oxygen was monitored daily. Other chemical analyses were conducted on irregular schedules as needed.

In addition to chemical analyses several physical parameters were monitored. Water temperatures were monitored daily with maximum-minimum thermometers and periodically with 8-day recording thermographs. The influent pressure required to maintain a constant hydraulic detention time was monitored with varying frequency throughout the study. Rotometers were calibrated against measured effluent flow rates. In addition tracer studies, using the chloride ion as a

tracer, were run when each unit was put on line, and approximately monthly thereafter. Pre- and post-injection density corrections were made using sodium sulfate. The tracer studies were analyzed using the volume apportionment techniques (17, 18).

Influent Quality

The tile drainage used for the investigation reported in this paper came from a drainage system that was in existence when the Center was constructed. This system, which services approximately 400 acres (160 ha), was chosen because of its proximity to land available for construction of the Center and the quality of the drainage which was considered to be quite "typical." Table 2 presents the range of constituent concentrations in this drainage. The variations are seasonal and due primarily to irrigation applications and rainfall. With the exception of the variation in nitrogen concentration, it was decided that all other constituents should be allowed to vary naturally. Sodium nitrate was added to the influent to each filter to maintain an average nitrate-nitrogen concentration of approximately 20 mg/l. (The nitrogen contained in tile drainage is essentially all in the nitrate form.)

Results and Discussion

As stated in the section on Experimental Procedures, the filter denitrification study at the Center was designed to answer five questions. The first four were accomplished roughly in sequence

by conducting the investigation in three phases. The fifth, because of its significance with regard to process cost, was studied during all segments of the investigation.

Phase One

The first phase of the subject experimentation, to determine if anaerobic filter denitrification was feasible under field conditions, was conducted using filters containing two sizes of activated carbon, washed sand, and 3/8-inch diameter aggregate. Table 3 presents a tabulation of all media investigated, the diameter of filters in which they were studied, and the hydraulic detention times at which they were operated for all phases of this research. All of the filters operated during the first phase of the study removed at least 80 percent of the nitrogen applied for a minimum of 30 consecutive days. Treatment efficiencies of filters containing the various media differed slightly. The process did work and the experimentation thus proceeded to its next phase, which was to determine the significance of medium size, texture, and sorptive quality. The original 18- and 36-inch diameter filters were constructed at this time.

Phase Two

The following media were selected for this phase: rounded aggregate (3/8- and 1-inch diameters); angular bituminous coal (5/16- and 1-inch diameters); volcanic cinders (5/16-, 5/8, and 1-inch diameters); 0.164-inch diameter activated carbon; and

washed sand. Aggregate offered a relatively smooth, nonporous, nonsorptive surface, in addition to being very durable. Coal has a limited sorptive capacity (19), and its irregular surface provided more surface area per unit volume than did the aggregate. Volcanic cinders were selected because, like coal, it is highly porous and roughly textured with a large surface area per unit volume, while its sorptive capacity is even less than that of coal. The activated carbon selected was the largest size available for study (0.164-inch diameter). It was used as an extreme in the investigation of the significance of sorptive quality. Sand was included because of its fineness of graduation and durability. It also provided a good extreme in the study of the significance of media sizes on anaerobic filter operation.

All units were operated with hydraulic detention times (based on void volumes) of 2 hours. The choice of this detention time was based on the results of the first phase of the investigation. The removal efficiencies for the filters operated for this phase of the study (July 1968 to October 1968) showed no appreciable difference in percent nitrogen removal (Table 4). The range of nitrogen removal efficiencies observed seemed to be due to equipment problems and not the process under study. It was apparent that the medium surface texture and sorptive quality did not appreciably affect removal efficiencies. There was also no apparent difference between the removal efficiencies of filters containing media of the same type

but of different sizes. For these reasons, and considering the relative merits of each medium, the 5/16-inch coal and 5/16-inch volcanic cinder filled filters were eliminated near the middle of October 1968.

Phase Three

The third phase of the investigation was begun at this time. This phase emphasized the effect of long term operation on unit efficiency and the minimization of hydraulic detention time. The filters that had contained the 5/16-inch coal and 5/16-inch volcanic cinders were refilled with washed sand and 1-inch aggregate, respectively. These units were operated with hydraulic detention times of 0.5 hours. In addition, two new 18-inch diameter filters were filled with washed sand and 1-inch aggregate, respectively, and operate with 1-hour hydraulic detention times. All of the filters remaining from the second phase were maintained as during that segment of the study.

The factors of importance when considering the effects of long-term unit operation are the influent pressure required to maintain a constant hydraulic detention time and changes in this pressure with time, changes in removal efficiency with time and temperature, and changes in the flow regime within the filter.

The influent pressures required to maintain a constant hydraulic detention time and the nitrogen removal efficiencies for this phase of the study are summarized in Table 5. The required pressure for the majority of the filters reached a level that remained quite constant and did not increase with the length of operation of the unit.

The influent pressure and nitrogen removal data for the sand-filled filter operated with a one-hour detention time are presented in Figure 4. Examination of this figure shows that by November 1, 1968 the required influent pressure exceeded 30 psig. Because of operating difficulties which developed with this required pressure, a surge of water was forced through the filter on November 4, 1968 to break up the bacterial mass. Prior to breaking up the bacterial mass, the filter's nitrogen removal efficiency had exceeded 90%. However, following it, the removal efficiency dropped to a low of 34%. This efficiency head loss relationship occurred again in December. The influent pressure again increased, to approximately 22 psig, while the removal efficiency of the unit also increased, to over 90% nitrogen removal. At this point, the nitrogen removal efficiency dropped to less than 20%, and then the pressure dropped to less than 10 psig. This unit was taken out of operation on January 9, 1969. During the same time period, the required influent pressure for a filter filled with 1-inch diameter aggregate and operated with a 1-hour hydraulic detention time never exceeded 5.5 psig with an average total nitrogen removal efficiency of 93% (Figure 5). The average nitrogen removal for the 1-hour detention sand filter for the same period was 58%.

The sand-filled filters operated with 1/2- and 2-hour detention times did not have the large variations in the required influent pressure that were found necessary for the one operated with 1-hour detention time. They did, however, have similar variations

in nitrogen removal efficiencies. This was assumed due to short-circuiting of the flows within the units. This assumption was verified by tracer studies and observation of the media upon dismantling the units. For example, upon emptying the unit operated with a theoretical hydraulic detention time of 2 hours, dark columns of bacteria extending to the filter surface were observed. The columns were approximately 3 inches in diameter with no indication of bacterial growth outside of them.

The filters containing the 3/8-inch aggregate, 5/8-inch volcanic cinders, and activated carbon did not experience hydraulic short-circuiting; however, the high influent pressures required by these units made them less economical than the 1-inch diameter media.

The overall removal efficiencies for the filter containing 1-inch diameter aggregate and operating with a 1-hour hydraulic detention time (Figure 5), did not have any significant trend during the period of operation covered by the data. This statement was also true for all but one of the filters operated during both Phases 2 and 3 of the Study (Table 4 and 5). The one exception, the sand-filled filter, with a 2-hour hydraulic detention time, did have a lower removal efficiency in the third phase of the study. The reason for this was at the long detention time it took until Phase 3 for short-circuiting to develop.

During the period of time covered by Phases 2 and 3 of the Study, the temperature of the influent to the units varied from a high of 22° to a low of 10° Centigrade. With such a wide variation

of influent temperatures there should have been an obvious reduction in the anaerobic filters' ability to denitrify, which cannot be seen in the data thus far presented. By grouping the nitrate and nitrite removal data for samples taken at different depths within a filter, as illustrated in Table 6, this reduction in efficiency did become apparent. As the temperature of the influent dropped, the percent of the filter bed required for the same degree of treatment increased. The 6-foot bed depths used for this investigation and the range of temperatures encountered were such that the effect was not reflected in the overall treatment efficiencies of the units. This information is only qualitative, since steady-state conditions were not reached at any given temperature. Additional study is currently (May 1969) being undertaken to quantify the effect of temperature on filter denitrification. This study is being conducted using a filter which has been constructed in a low temperature incubator.

Figure 6 presents "typical" results for tracer studies conducted on the various filters containing 1-inch diameter aggregate. The results of tracer studies conducted at different times during the operation of these units were essentially identical to those presented in the figure. The curves are for a step change in tracer concentration and show that 75 to 90% of the response was attributable to plug flow.

The average nitrogen removal efficiency of the 1-inch diameter aggregate-filled filter operated with a 0.5 hour detention time, during Phase 3 of the Study, was only 75%. However, considering the data

presented in Table 6, it is assumed that this unit was adversely affected by the low temperatures of the influent. This detention time may be adequate for effective treatment during the warmer seasons of the year. This assumption is currently under investigation, as is the possibility of using media of greater than 1-inch diameter.

Carbon Source

As previously mentioned, a biodegradable organic carbon source is essential for the process, and methanol was used for this purpose in this investigation. The following equation was developed by McCarty, et al from theoretical half reactions and a consumptive ratio[1/] which was determined experimentally with semi-continuous laboratory cultures (6).

$$C_m = 2.47\ N_o + 1.53\ N_1 + 0.87\ D_o$$

C_m = required methanol concentration, mg/l.

N_o = initial nitrate-nitrogen concentration, mg/l.

N_1 = initial nitrite-nitrogen concentration, mg/l.

D_o = initial dissolved oxygen concentration, mg/l.

Making an allowance for the variable dissolved oxygen content of the waste being treated (7 to 9 mg/l) the equation predicts that 55.5 to 57.2 mg/l of methanol would be required to remove 20 mg/l nitrate-nitrogen.

1/Consumptive ratio--the ratio of the total quantity of an organic chemical consumed during denitrification to the stoichiometric requirement for denitrification and deoxygenation alone.

Because the equation was developed in semi-continuous laboratory cultures and not anaerobic filters operating under field conditions, its applicability to this investigation was not known. During the initial portion of the first phase of this study 100 mg/l of methanol were added to the influent of each filter. The amount over and above the calculated required concentration was added as a margin of safety. After it was shown that the process actually did work under field conditions and that substantial quantities of methanol were present in the effluents of the various units, the influent methanol concentration was lowered in steps, while monitoring nitrogen removal efficiencies and effluent methanol concentrations. At present, a constant influent methanol concentration of 65 mg/l are being used at the Center. This concentration is a compromise between actual need and practicality. Until an automatic system of controlling methanol addition in proportion to influent nitrate- and nitrite-nitrogen and dissolved oxygen is developed, work on further minimizing the amount of methanol used is considered impractical under field conditions. This study has shown that with such a system the methanol dosage could be reduced and that the equation is applicable. During this study, while operating as described above, effluent methanol concentrations ranged from 0 to over 10 mg/l depending on variations in the character of the influent.

SUMMARY AND CONCLUSIONS

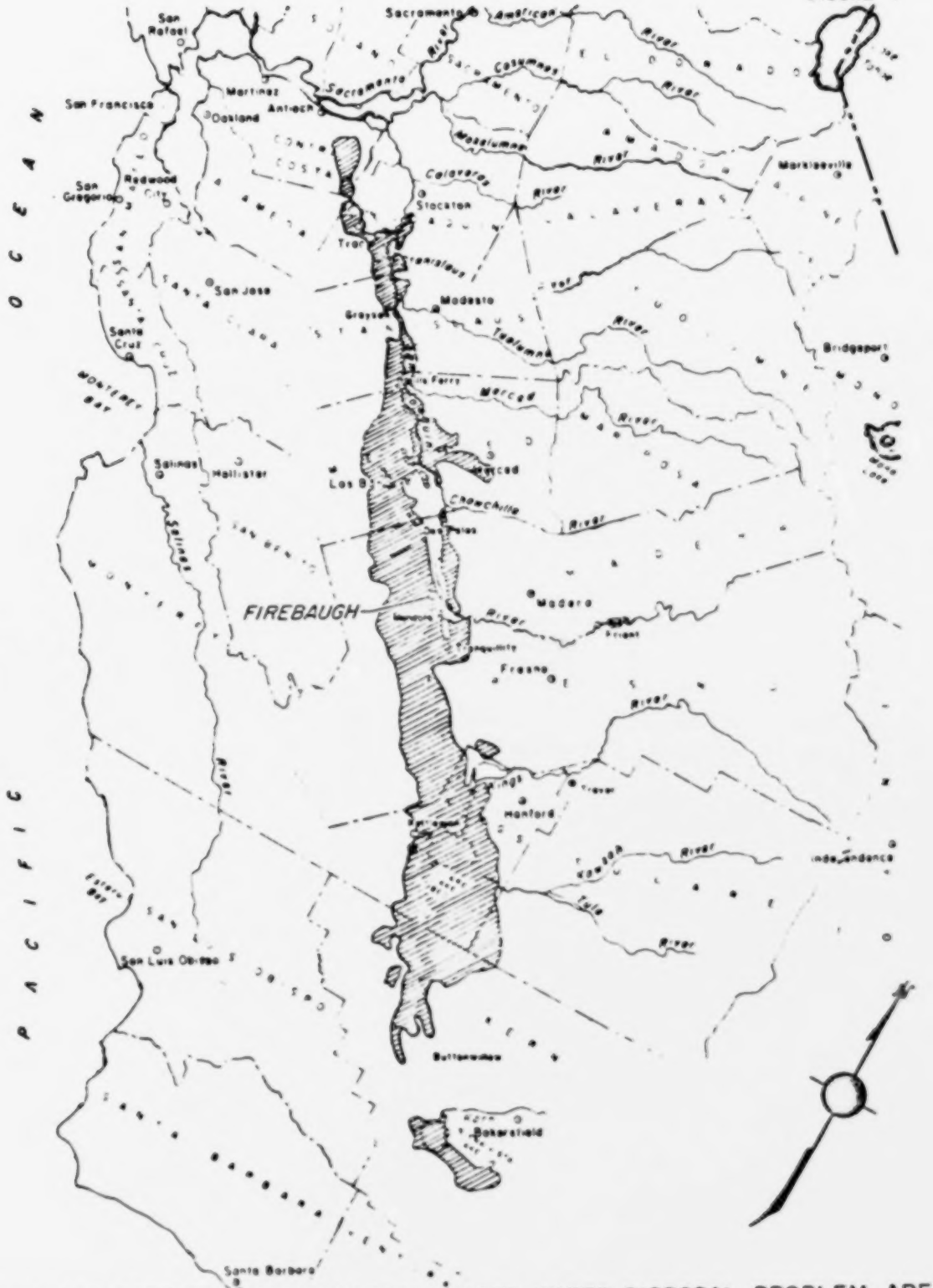
The material presented describes the operation of upflow anaerobic filters operated to determine if nitrate-nitrogen could be efficiently removed from the subsurface agricultural drainage of the San Joaquin Valley by anaerobic denitrification. Filters of three sizes (4-, 18-, and 36-inch diameters) were operated under field conditions with hydraulic detention times from 0.5 hour to 6 hours. Various media were investigated, ranging from fine activated carbon to 1-inch diameter aggregate. The required concentration of influent biodegradable organic carbon was also investigated.

The following conclusions are drawn from the results of the research described:

1. San Joaquin Valley subsurface agricultural drainage can be efficiently denitrified using the anaerobic filter process.
2. The sorptive characteristics of the filter medium used has no apparent effect on the nitrogen-removal efficiency of the process.
3. Use of media of less than 1-inch diameter in upflow anaerobic filters results in high head losses and/or low nitrogen removal and such media are not advisable.
4. Depending on temperature, efficient nitrate removal can be accomplished with hydraulic detention times of 0.5 hour to 2 hours.

5. Long-term operation is feasible without the need for backwashing, etc.
6. The equation for the quantity of methanol required for denitrification developed by McCarty, et al using semi-continuous laboratory cultures is also applicable to anaerobic filters operating under field conditions.

FIGURE 1



EXISTING AND POTENTIAL AGRICULTURAL WASTE WATER DISPOSAL PROBLEM AREAS
SAN JOAQUIN VALLEY - CALIFORNIA

SCALE OF MILES
10 0 0 20 30 40

TABLE 1

ESTIMATED CHARACTERISTICS OF SAN LUIS DRAIN WATERS

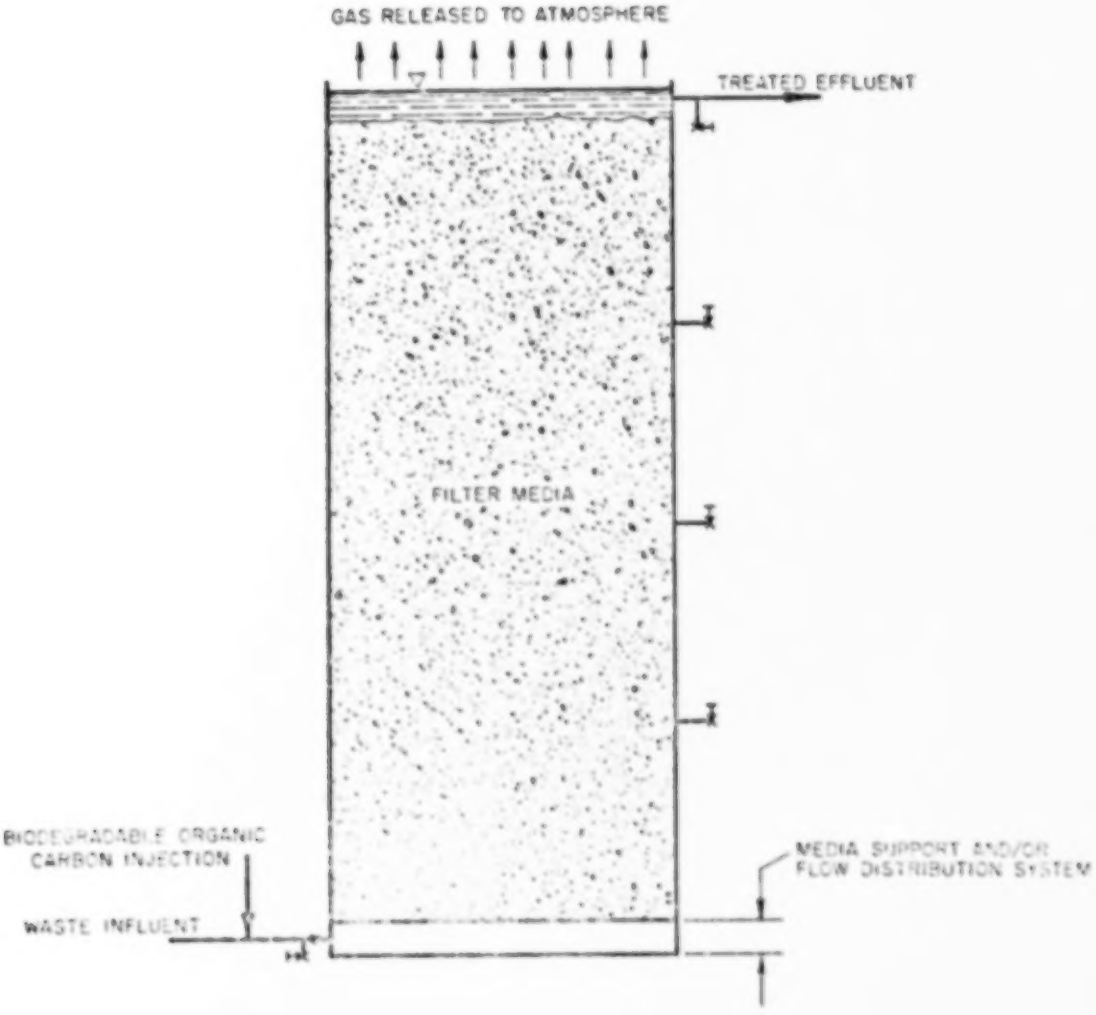
Constituent	1970 Conditions mg/l	2020 Conditions mg/l
Total Dissolved Solids	7,000	3,000
Salts		
Sulfate	3,000	700
Sodium	1,500	700
Chloride	1,200	900
Calcium	300	100
Magnesium	200	50
Bicarbonate	200	100
Potassium	20	10
Boron	10	3
Nutrients		
Nitrogen	20	20
Phosphate	0.15	0.15
Pesticides	<0.001	<0.001
Others		
5 Day BOD	1-3	1-3
COD	10-20	10-20

TABLE 2

CHARACTERISTICS OF TILE DRAINAGE USED AT THE INTERAGENCY AGRICULTURAL WASTE WATER TREATMENT CENTER

Constituent	Range of Concentrations mg/l
Total Dissolved Solids	2500 - 7600
Salts	
Sulfate	1500 - 3900
Sodium	620 - 2050
Chloride	310 - 640
Calcium	160 - 390
Magnesium	70 - 230
Bicarbonate	280 - 330
Potassium	4 - 11
Boron	4 - 15
Nutrients	
Nitrogen	5 - 25
Phosphate	0.13 - 0.33
Pesticides	<0.001
Others	
5 Day BOD	1 - 3
COD	10 - 20
DO	7 - 9

FIGURE 2



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LEGEND

I OPTIONAL SAMPLE TAPS

SCHEMATIC DIAGRAM
UPFLOW ANAEROBIC FILTER DENITRIFICATION PROCESS

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Figure 3. 18-INCH DIAMETER ANAEROBIC FILTERS

TABLE 3

SUMMARY OF MEDIA, HYDRAULIC DETENTION TIMES, AND ANAEROBIC FILTER DIAMETERS STUDIED

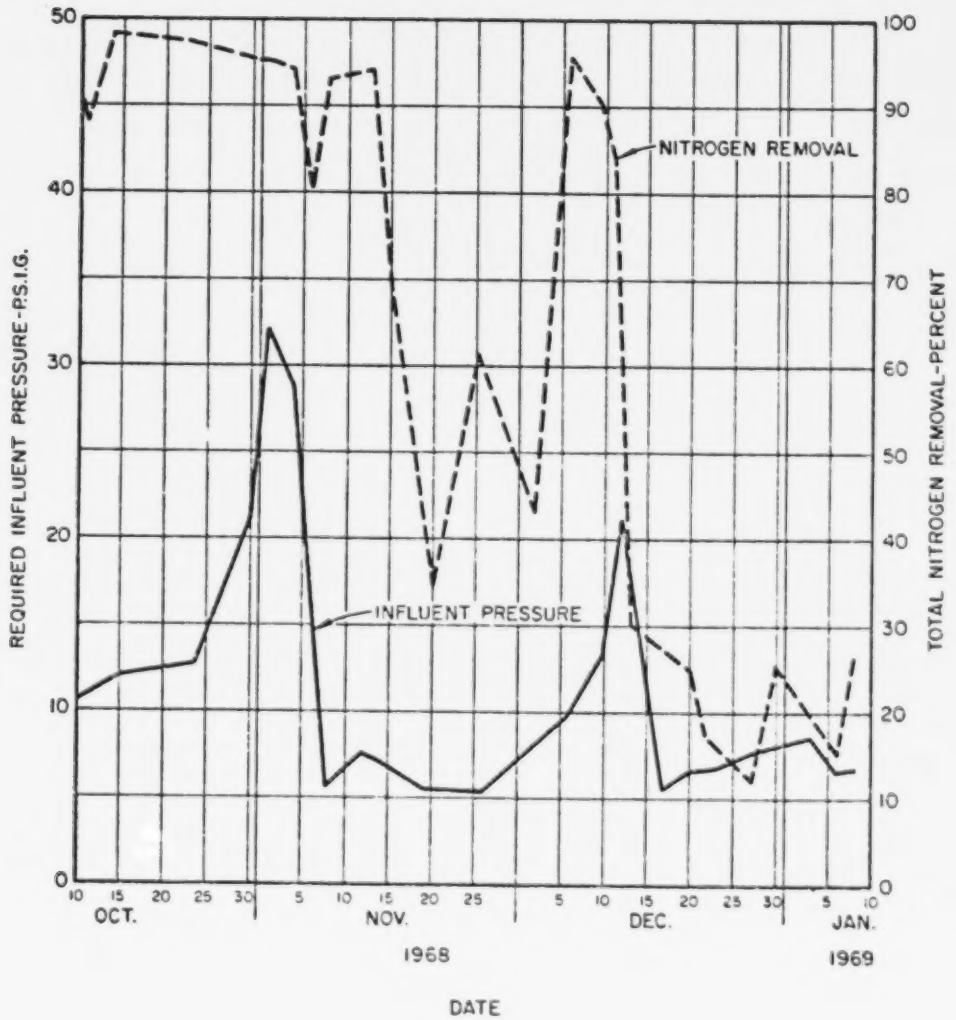
Medium	Mean Medium Diameter, Inches	Hydraulic Detention Time, Hours	Anaerobic Filter Diameter Inches
Activated Carbon	0.067	6 and 2	4
	0.164	6 and 2	4 and 18
Washed Sand	0.012	6,2,1, and 0.5	4 and 18
Rounded Aggregate	0.375	6 and 2	4 and 18
	1.00	2,1, and 0.5	
Bituminous Coal	0.312	2	18
	1.00	2	18
Volcanic Cinders	0.312	2	18
	0.625	2	36
	1.00	2	18

TABLE 4

NITROGEN REMOVAL EFFICIENCIES FOR PHASE TWO

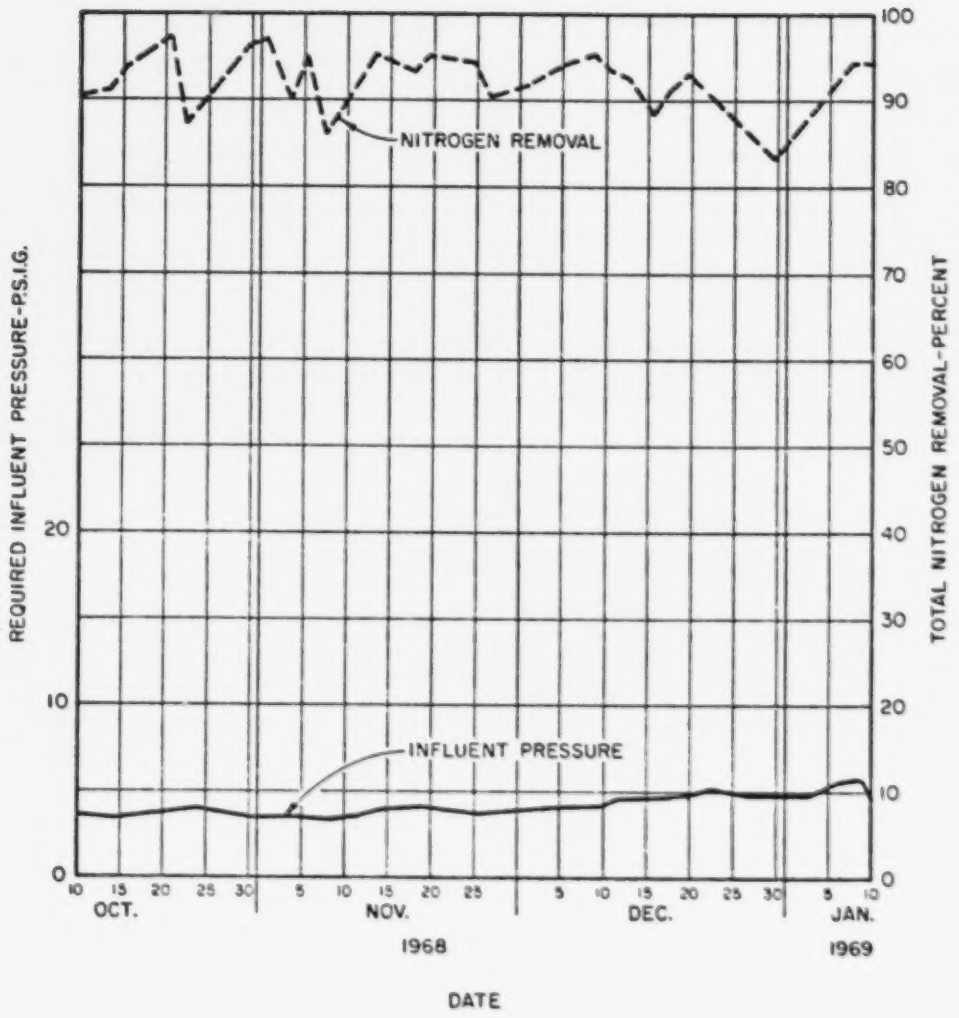
Medium	Nitrogen Removal Efficiency, Percent		
	Min.	Max.	Average
Activated Carbon	89	99	96
Washed Sand	84	97	93
5/16" Coal	80	98	93
5/16" Volcanic Cinders	85	98	94
3/8" Aggregate	82	97	94
5/8" Volcanic Cinders	87	97	91
1" Coal	81	98	93
1" Volcanic Cinders	89	97	96
1" Aggregate	89	98	94

FIGURE 4



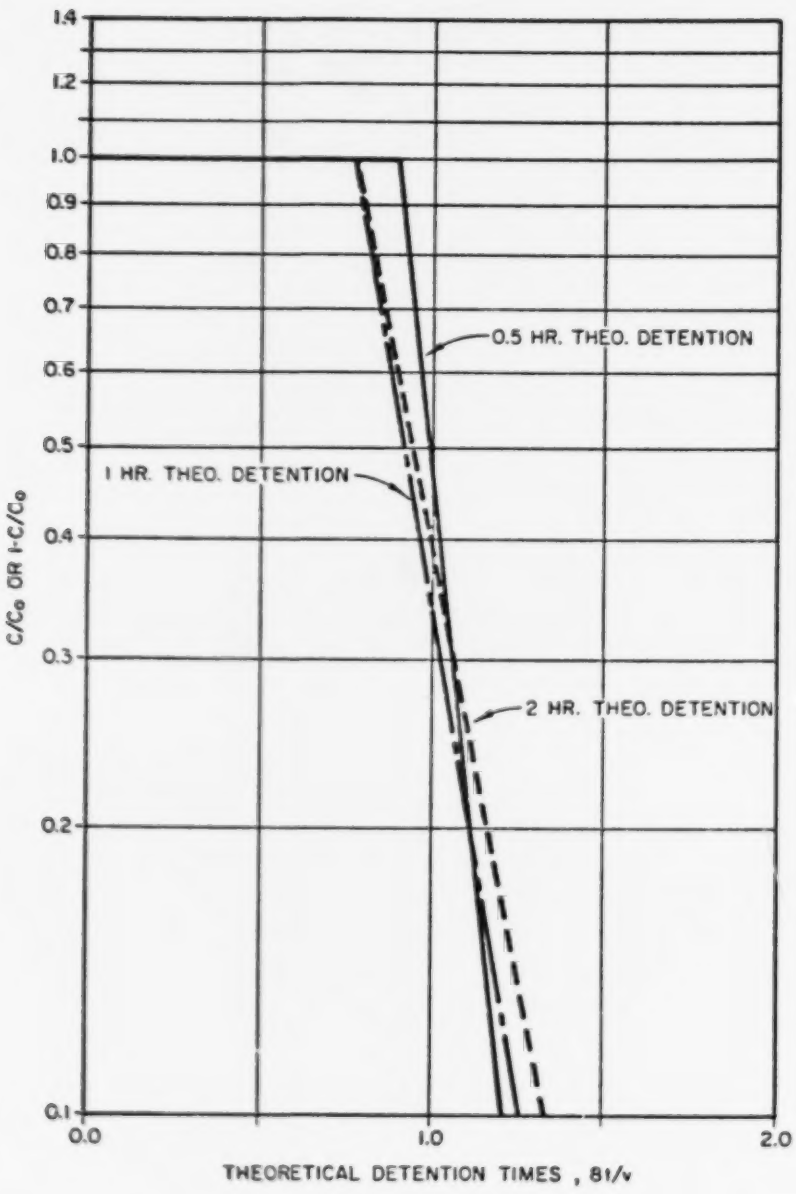
TOTAL NITROGEN REMOVAL AND INFLUENT PRESSURE VERSUS TIME
FOR SAND FILLED 18-INCH DIAMETER FILTER WITH ONE HOUR DETENTION

FIGURE 5



TOTAL NITROGEN REMOVAL AND INFLUENT PRESSURE VERSUS TIME
FOR 1-INCH AGGREGATE FILLED 18-INCH DIAMETER FILTER
WITH ONE HOUR DETENTION

FIGURE 6



RESULTS OF TRACER STUDIES ON ANAEROBIC FILTERS
CONTAINING 1-INCH DIAMETER AGGREGATE

TABLE 5

REQUIRED INFLUENT PRESSURES AND NITROGEN REMOVAL EFFICIENCIES FOR PHASE THREE

Medium	Hydraulic Detention Time, Hours	Length of Operation 1/ Days	Required Influent Pressure, P.S.I.G			Nitrogen Removal Efficiency, Percent		
			Min.	Max.	Average	Min.	Max.	Average
Activated Carbon	2.0	193	7.0	15.4	11.7	86	98	96
Washed Sand	0.5	51	4.1	6.2	5.2	0	95	19
	1.0	93	5.5	32.0	10.6	12	98	58
	2.0	183	4.9	12.1	8.1	23	96	82
3/8" Aggregate	2.0	182	9.6	21.5	15.4	91	97	95
5/8" Volcanic Cinders	2.0	138	8.3	12.0	10.6	60	97	89
1" Coal	2.0	132	4.0	7.8	6.0	81	97	93
1" Volcanic Cinders	2.0	130	3.1	6.8	5.1	85	98	95
1" Aggregate	0.5	92	2.5	6.6	4.7	53	91	75
	1.0	106	3.2	5.5	4.2	80	97	92
	2.0	183	3.5	7.5	5.5	84	97	93

1/ Phases 2 and 3 combined where applicable.

TABLE 6

PROFILE DATA GROUPED BY PERCENT OF FILTER REQUIRED FOR 80% OR GREATER NO_3+NO_2 REDUCTION

(1 inch diameter aggregate media, 2-hour hydraulic detention time)

Percent of Filter Used	Average Influent Temperature °C
25% or less	14.5
25% to 50%	12.8
50% to 75%	11.9

APPENDIX I - REFERENCES

1. Stetson, C. L., "A Drainage System for the San Joaquin Valley," 4th International Water Quality Symposium, San Francisco, California (August 14, 1968).
2. Price, E. P., "The San Luis Drain," 4th International Water Quality Symposium, San Francisco, California (August 14, 1968).
3. San Francisco Bay-Delta Water Quality Control Program, Preliminary Edition of Final Report by Kaiser Engineers et al. to the State of California (December 1968).
4. "Effects of the San Joaquin Master Drain on Water Quality of the San Francisco Bay and Delta," U. S. Department of the Interior, Federal Water Pollution Control Administration, Southwest Region, San Francisco, California (January 1967).
5. Hutchinson, G. E., A Treatise on Limnology-Volume 1, John Wiley and Sons, Inc., New York, New York (1957).
6. McCarty, P. L., Beck, L. A., and St. Amant, P. P., "Biological Denitrification of Waste Waters by Addition of Organic Materials," 24th Industrial Waste Conference, Purdue University, Lafayette, Indiana (May 1969).
7. Christenson, C. W., et al.,"Reduction of Nitrate-Nitrogen by Modified Activated Sludge," USAEC, TID. 7517, Pages 264-267 (1956).
8. Ludzack, F. J., and Ettinger, M. B., "Controlling Operation to Minimize Activated Sludge Effluent Nitrogen," Journal Water Pollution Control Federation, Vol. 34, No. 9, Pages 920-931 (1962).

9. Bishop, D. F., "Ammonia and Nitrogen Removal," Internal Report, Advanced Treatment Research, FWPCA, R. A. Taft Water Research Center, Cincinnati, Ohio.

10. Finsen, P. O., and Sampson, D., "Denitrification of Sewage Effluents," Water and Waste Treatment Journal, Vol. 7, pages 298-300 (1959).

11. Young, J. C., and McCarty, P. L., "The Anaerobic Filter for Waste Treatment," Stanford University, Technical Report No. 87, Stanford, California (March 1968).

12. McCarty, P. L., "Feasibility of the Denitrification Process for Removal of Nitrate-Nitrogen from Agricultural Drainage Waters," Appendix California Department of Water Resources Bulletin 174-3 (May, 1969).

13. "Standard Methods for the Examination of Water and Wastewater," American Public Health Association, Inc., New York, New York, 12th Edition (1965).

14. Boos, R. N., "Quantitative Colormetric Microdetermination of Methanol with Chromotropic Acid," Analytical Chemistry, Vol. 20, pp. 964-965 (1958).

15. Synthetic Methanol, Commercial Solvents Corporation, Industrial Chemicals Department (1960).

16. Beyer, G. B., "Spectrophotometric Quantitative Determination of Methanol and Distilled Spirits," Journal of the Association of Agricultural Chemists, Vol. 34, pp. 745-755 (1951).

17. Cholette, A., Blanchet, J., and Cloutier, L., "Performance of Flow Reactors at Various Levels of Mixing," Canadian Journal of Chemical Engineering, Vol. 38, (1960).

18. Milbury, W. F., "A Development and Evaluation of a Theoretical Model Describing the Effects of Hydraulic Regime in Continuous Microbial Systems," dissertation presented to Northwestern University at Evanston, Illinois, in 1964, in partial fulfillment of the requirement for the degree of Doctor of Philosophy.

19. "Summary Report--The Advanced Waste Treatment Research Program--January 1962 through June 1964," U. S. Department of Health, Education, and Welfare, Public Health Service, Division of Water Supply and Pollution Control, PHS Publication No. 999-WP-24 (April 1965).